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AN OBSERVATIONAL SEARCH FOR LARGE-SCALE ORGANIZATION OF FIVE-MI--ETC(U)
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AN OBSERVATIONAL SEARCH FOR LARGE-SCALE ORGANIZATION OF FIVE-MINUTE OSCILLATIONS ON THE SUN

By

Phil H. Dittmer
Philip H. Scherrer

and

John M. Wilcox

Office of Naval Research
Contract N00014-76-C-0207

National Aeronautics and Space Administration
Grant NGR 05-020-559

National Science Foundation
Grant ATM74-19007
Grant DES75-15664

and

The Max C. Fleischmann Foundation

SUIPR Report No. 709

July 1977

INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

(14) SU-IPR-8Ø9

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: SUIPR Report No. 809	2. GOVT ACCESSION NO	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) An Observational Search for Large-Scale Organizations of Five-Minute Oscillations on the Sun.		5. TYPE OF REPORT & PERIOD COVERED: ~~Scientific~~; (9) Technical rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): (10) Phil H. Dittmer, Philip H. Scherrer [redacted] John M. Wilcox		8. CONTRACT OR GRANT NUMBER(s): N00014-76-C-0207, (15) NGR-05-020-559
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Institute for Plasma Research, Stanford University, Stanford, California 94305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (12) 22p.
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Electronics Program Office, Arlington, Virginia 22217		12. REPORT DATE: (11) Jul[redacted]77 — 13. NO. OF PAGES: 22
		15. SECURITY CLASS. (of this report): Unclassified
14. MONITORING AGENCY NAME & ADDRESS (if diff. from Controlling Office)		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this report)

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18. SUPPLEMENTARY NOTES

Tech; Other

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Five-Minute Oscillations
Large-Scale Solar Velocity Field

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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19. KEY WORDS (Continued)

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...ed to: Solar Physics

Solar Physics

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Abstract

The large-scale solar velocity field has been measured over an aperture of radius 0.8 $R_{\odot}$ on 121 days between April and Septem'er, 1976. Measurements are made in the line FeI 5123.730 Å, employing a velocity subtraction technique similar to that of Severny et al. (1976). Comparisons of the amplitude and frequency of the five-minute resonant oscillation with the geomagnetic C9 index and magnetic sector boundaries show no evidence of any relationship between the oscillations and coronal holes or sector structure. The average period measured for the five-minute oscillation is 312.0 ± 0.9 sec, which is longer than the average 296.1 ± 1.3 sec period originally reported by Noyes and Leighton (1963) from measurements in the line CaI 6103. The average amplitude is 2.0 m/s, which agrees reasonably with the 2.4 m/s value reported by Fossat and Ricort (1975). This amplitude is larger than might have been expected from an extrapolation of the work of Tanenbaum et al. (1969) to a large aperture, and is evidence of a large horizontal wavelength for the oscillations.

Solar Physics

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Observational evidence for a coronal temperature well above the photospheric temperature has existed now for thirty-five years (Edlen, 1943). The most popular explanation for the source of this high temperature is still that of Bierman (1946 and 1948) and Schwarzschild (1948) who independently suggested that subphotospheric turbulance would generate acoustic waves that would steepen into shocks as they propagated upward, depositing their energy in the chromosphere and corona. Though there have been some reports of periodic (Chipman, 1976; Athay et al., 1976) or aperiodic (Billings, 1959; Vernazza, 1975) disturbances in the transition region or corona (see also Liu, 1974; Deubner, 1976), further observational evidence that turbulence-generated acoustic waves are indeed responsible for high coronal temperatures would be desirable.

The existence of large-scale structure in the corona as indicated by coronal holes (Munro and Withbroe, 1972; Altschuler et al., 1972) makes it appropriate to investigate the possibility that a different level of mechanical energy input could be associated with such large-scale structures. Current models of coronal holes (Adams and Sturrock, 1975; Rosner and Vaiana, 1976) succeed in explaining different coronal temperatures on the basis of different magnetic field configurations, with constant energy input assumed. The success of these theories does not preclude the possibility that differences in energy input could also be involved, either directly in producing the observed differences in coronal temperature or indirectly by having an influence on whether coronal field lines are open or closed.

The five-minute resonant oscillation in the solar photosphere and lower chromosphere provides a convenient means of measuring mechanical energy flux. Not only does the resonant character of the oscillation facilitate its separation from instrumental noise, but it has also been suggested (Leibacher and Stein, 1974) that waves at such longer periods might theoretically be expected to be primarily responsible for heating the upper chromosphere or corona. The purpose of the present investigation has therefore been to search for large-scale changes in amplitude or period of the five-minute oscillations that might be related to coronal holes or the magnetic sector structure, or to other large-scale solar structures.

Apparatus and Method

Observations were conducted using the mean field telescope and Babcock magnetograph of the Stanford Solar Observatory. This telescope is especially designed for synoptic observations of large-scale solar magnetic and velocity fields of very small amplitude. The technique used was an adaptation of the modification used by Severny et al. (1976) which enables the magnetograph to be used directly to measure the velocity difference between two portions of the solar disk. Since the magnetograph measures line-of-sight magnetic fields by measuring the difference in wavelength between the right and left circularly polarized components of a magnetically sensitive absorption line, if one uses the magnetically insensitive line FeIλ5123.730 Å and positions optics which causes light from the center (limb) of the disk to be right (left) circularly polarized, the magnetograph signal then gives a measure of the wavelength difference between the center and limb of the disk. This wavelength difference can be calibrated in terms of the difference in line-of-sight velocity between center and limb. Since the five-minute oscillation has a horizontal scale size small compared to the aperture used, making center and limb essentially independent, and since subtraction of the limb velocities is equivalent to shifting the phase by π, the velocity difference measured is essentially the same as if the average velocity were measured over center and limb.

In the present investigation, the center of the disk was defined to be the region extending from disk center out to a radius of 0.50 $R_{\odot}$, and the limb was the region between radius 0.55 $R_{\odot}$ and 0.80 $R_{\odot}$. The velocity difference and intensity signals were measured in 15.0 second integrations and recorded on magnetic tape for analysis. Plots of intensity and velocity difference were made for each observation, which permitted removal of occasional spurious deviations in the signal.

Slow drifts of amplitude 10-30 m/s were generally present in the signal, which were probably produced by heating of the telescope support structure over the course of the day which caused the solar image to shift position relative to the polarizing optics or spectrograph. Such drifts were at periods much longer than five minutes, and should therefore have had little influence on the measured period or amplitude of the five-minute oscillations.

The five-minute oscillations could be identified on individual records with peak-to-peak amplitude of about 5-10 m/s. In order to obtain more quantitative information regarding their amplitude and period, power spectra were computed from each observation. The data were first fitted to a straight line and the fit subtracted to remove the effect of baseline shifts and slow signal drifts, since power spectrum algorithms require that the signal is stationary and of zero mean. The autocorrelation was then computed out to a lag of 50 minutes (200 integrations of 15.0 seconds) in the usual manner (Blackman and Tukey, 1958). The power spectrum was then found by taking the cosine transform of the power spectrum and smoothing with a hanning window. A total of 128 power spectra were computed from observations between April 13, 1976 and September 21, 1976, with a total of 475 hours of observations on 121 different days. On two occasions, calibration showed that a misalignment of the wave-plate retarders and linear polarizers used to produce circularly polarized light had produced a loss of instrumental sensitivity, which resulted in 10 days being excluded from analysis. Excepting these two periods, observing weather was so good that only eight days of observation were missed between April 13 and July 30. A total of 40 days were missed in the interval of 161 days. If more than one observation was conducted on a given day, the average power spectrum was calculated with weighting for the length of the individual observations.

The Search for Large-Scale Organization

In order to search for large-scale organization of the five-minute oscillations, each power spectrum was characterized by four parameters:

The peak power--the maximum amplitude of power measured in the interval of periods from 3 1/3 min to 10 min.

The noise power--the integrated power over the frequency range 5.0 mHz to 8.33 mHz, corresponding to periods of 3 1/3 min to 2 min. This power was almost certainly of instrumental rather than solar origin, and was included more as a check on later analysis procedures than as a source of information on solar oscillations at periods between 120 sec and 200 sec.

The signal power--the integrated power over the frequency range 1.67 mHz to 5.0 mHz corresponding to periods of 10 min to 3 1/3 min, with the noise power subtracted.

The average resonant frequency--the average frequency of the resonant peak in the 1.67 mHz to 5.0 mHz interval. Correction was made for the noise power by taking the average power above the noise rather than above zero, in the following manner:

$$\frac{1}{f_2 - f_1} \int_{f_1}^{f_2} (P(f) - P_n)\, f\, df$$

where $f_1 = 1.67$ mHz, $f_2 = 5.0$ mHz, $P(f)$ is the power measured at frequency f, and P_n is the noise power per frequency interval measured in the frequency range 5.0 mHz to 8.33 mHz as described above. The calculation of these parameters is illustrated in Figure 1.

The result was that each day's observation was characterized in terms of four numbers which could be compared with the magnetic sector structure, with coronal holes, or with each other in search of large-scale organization. The first such comparison performed was a superposed epoch analysis about magnetic sector boundaries as determined by changes in polarity of the sun's mean magnetic field as measured at the Stanford Solar Observatory. The boundary was assumed to be located between two days of opposite polarity, and the average value of the parameter of interest was computed for all days immediately preceding a boundary, for all days two days before a boundary, and so on until an interval of ± 7 days about the boundary was included. In performing the averaging, each parameter was weighted for the length of the observation. The superposed epoch of each of the four parameters computed is shown in Figure 2, along with the grand average for each parameter and the computed error bar. In each case, it is evident that there is no organization of the parameter about sector boundaries. In addition, the number of daily averaged values falling within one error bar of the grand average is in every case comparable to the 68.3% value expected for a normally distributed random variable.

Though coronal holes are quite closely related to magnetic sector boundaries (Sawyer, 1976; Wagner, 1976) it seemed desirable to compare the five-minute oscillation data described herein with a more direct measure of the presence of the coronal holes themselves. Since ground based Heλ10830 observations of coronal holes were not available during much of the summer of 1976, the geomagnetic C9 index was used for this comparison, since Sheeley et al. (1976) have shown that this index is very closely correlated with solar wind speed and the presence of equatorial coronal holes. In addition, comparison was made with the magnitude of the sun's mean magnetic field as measured at Stanford since comparison has shown it to be quite well correlated with the C9 index. Following Bevington (1969), the correlation coefficient was calculated between the number identifying coronal hole occurrence (the C9 index or the magnitude of the mean solar field) and the signal power or average frequency measured for the five-minute oscillation. Since the C9 index is measured at UT1200 and measurements of the five-minute oscillations were centered around local noon at UT2000, the former was lagged in time by five days to approximate the expected 4½ day solar wind transit time. The correlation coefficients and probabilities of being drawn from parent populations with no correlation are as follows:

coronal hole identifier	five-minute oscillation parameter	r	P(ρ=0)
|mean field|	signal power	0.120	0.20
C9	signal power	-0.129	0.16
C9	average frequency	-0.0412	0.66
|mean field|	average frequency	0.110	0.24
mean field	signal power	-0.0456	0.63
mean field	average frequency	0.131	0.16

The expression used to calculate the probability that the sample was taken from an uncorrelated parent population (ρ=0) was also taken from Bevington. It is clear that there is no evidence for any correlation between the quantities considered.

Since no evidence was found for organization of five-minute oscillations with relation to magnetic sector boundaries or coronal holes, the question of whether there was any large-scale organization of the oscillations was next investigated. The four parameters chosen for each day's observations were used to calculate autocorrelations and power spectra in a search for periodicities near 27 days or integer fractions of 27 days to see if there was any large-scale ordering of the oscillations of sufficient persistence to co-rotate with the sun. The results showed a conspicuous lack of any long-term organization, with periods integer fractions of 27 days in no way outstanding.

Correlation coefficients were also calculated between the different measured five-minute oscillation parameters to see if, for example, there was a connection between longer periods and smaller amplitudes The results for the four parameter (six parts in all) are:

parameters	r	P(ρ=0)
signal power - noise power	0.0186	0.84
signal power - average frequency	0.0139	0.88

signal power - peak power	0.835	3.7×10^{-9}
noise power - average frequency	-0.104	0.26
noise power - peak power	0.124	0.18
average frequency - peak power	-0.103	0.27

There is no evidence for any correlation between the parameters with the conspicuous exception of the correlation between signal power and peak power, which is to be expected. The lack of correlation between signal power and noise power provides encouraging evidence that the definition of signal power used is essentially free from contamination by noise, and also indicates that observed variations are not due simply to changes in instrumental sensitivity, since these would affect signal and noise power in the same manner. The correlations were also calculated without weighting for the length of observation, and the only important difference was an increase of the correlation coefficient between noise power and peak power to 0.236, which has $P = 0.010$ of being drawn from an uncorrelated parent population. It is reasonable that records with greater noise levels might have higher resonant peaks, and that this effect would be more noticeable without weighting for length of observations since shorter observations would have higher noise levels.

A final search for large-scale organization was made using the power spectra themselves instead of some parameter. A superposed epoch of the power spectra about polarity reversals of the mean solar magnetic field was performed, with the result shown in Figure 3. The power spectrum at day -1 is the average of all power spectra on days immediately preceding a polarity reversal, with weighting for the length of observation, and similarly for the others. Though small variations can be seen in the average taken at different intervals from the polarity reversal, no obvious organization is present, and 453 of the 714 points or 63.4% are within one error bar of the grand average, which is close to the 68.3% expected for normal statistical fluctuations. More impressive than any differences is the similarity of the different power spectra, which gives evidence of the high quality of the observations and the relatively small statistical fluctuations resulting from the large number of hours of observations that were used.

General Characteristics of Five-Minute Oscillations

The conclusion of the preceding portion of the study is that there is no large-scale organization of five-minute oscillations related to the magnetic sector structure or coronal holes and there is no evidence of any large-scale organization of the oscillations. Since five-minute oscillations have not been conclusively identified as the agent for coronal heating, this does not prove that there is uniform energy input, nor do observed differences in coronal temperature preclude the five-minute oscillations from being the source of high coronal temperatures since, as mentioned previously, theorists have been able to account for such features as coronal holes even with an assumed uniform energy input. Attention was next directed to the oscillation data as an ensemble to determine whether or not any information could be gained as to the general character of the oscillations. Two features were slightly different than expected from smaller scale observations which are worthy of mention.

One unexpected result was that the period determined from these observations was consistently slightly longer then 300 seconds. Using the average frequency as measured above for the individual power spectra, the average period for the entire set of observations was found to be 312.9 ± 0.9 sec. A slightly different definition of the average frequency was then used, defining the average to be the centroid of the resonant peak, with the peak defined to be the power above the noise level rather than by using the 1.67-5.0 mHz interval. The average over the data set was 312.1 ± 1.3 sec. If the frequency of the resonant peak was used, a slightly longer average period of 320.2 ± 2.2 sec was found, indicating a slight asymmetry in the resonant peak due to the high frequency tail which becomes dominant at higher levels in the atmosphere. Every period determination gives a result longer than the value of 296.1 ± 1.3 sec reported by Noyes and Leighton (1963) from observations in the CaI λ6103 line. The difference in measured period is not large --- only about 5% --- but is much larger than the statistical errors in both sets of measurements.

The use of different spectral lines is unlikely to explain the longer period since the CaI $\lambda6103$ line is formed low in the photosphere (see Figure 1 of Noyes and Leighton) as is the FeI $\lambda5124$ line. In addition, Howard (1962) also measured a 296 sec period using the FeI $\lambda5250$ line which is formed at least as low as FeI $\lambda5124$ (Athay, 1976, p. 170), which would mean that its period should be at least as long were identical apertures used. Howard's measurement also makes it unlikely that the longer period found herein is due to use of different techniques to define the average period, since Howard determines the period from the secondary maximum in the autocorrelation function, which is closely related to the peak in the power spectrum. Secondary maxima in autocorrelation computed using the present data consistently indicated a period longer than five minutes. The most likely explanation is that the longer measured period is due to the large aperture size, though other possibilities such as a solar cycle change in period cannot be ruled out. Attempts to detect a shorter period by using apertures of $(3')^2$ and $(30'')^2$ were not successful, so if a shift in period with aperture size is present, it must occur between 5" and 30". Such a shift should be measured in observations using the same line and apertures of different sizes before it is accepted. The physical significance of this 5%, 10σ difference is not clear, but the shift to longer periods for larger apertures does at least agree in sign with the direction of the diagonal lines in the k-ω diagram of the Ulrich (1970) model.

The other general characteristic of the oscillations measured herein with a result somewhat different than might have been expected from small-scale observations is the amplitude. If all the power spectra are averaged together with weighting for the length of the individual observations, the rms amplitude, measured in the same manner as illustrated in Figure 1, is found to be 2.0 m/s. This result agrees well with the value of $V_{rms} = 2.4$ m/s published by Fossat and Ricort (1975a). Since they used the line NaI $\lambda5896$ (D_1) for which Deubner (1971) has estimated the oscillations to have 1.5 times the amplitude they have in FeI $\lambda5124$, and since the Nice group used an aperture including the full disk, they might be expected to record an amplitude $1.5 \times 0.8 = 1.2$ times as large as presently reported. Difference in analysis or in definition of five-minute power probably mean that agreement is not as good as it appears.

Comparison with smaller scale measurements requires knowledge of how the oscillatory amplitude scales with aperture size. Tanenbaum et al. (1969; see also Tanenbaum, 1971) derived an amplitude α (diameters)$^{-1}$ rule for apertures of dimensions larger than the average cell size. This derivation was based on the fact that N identical harmonic oscillators with random phase, the ensemble average varies as $N^{-\frac{1}{2}}$, so for a slit one would expect the amplitude to vary as (length)$^{-\frac{1}{2}}$ and for a round or square aperture, the amplitude should vary inversely with the linear dimension of the aperture. For a spherical sun, oscillating elements will no longer contribute equal signals because of the effects of limb darkening, foreshortening, and the decreasing line-of-sight component of radial velocity as one approaches the limb. The ensemble average will now be equal to the square root of the sum of the squares of the contributions from individual elements. Using this approach, calculations were made of the amplitude to be expected with the present instrument for independent elements of various dimensions, and the 2.0 m/s amplitude reported above would be consistent with an average region of radius 14500 km, corresponding to a square of length 25700 km. This calculation is based on an assumed amplitude of 100 m/s for an independent region, which is certainly too large an amplitude for a region of such large dimensions. Measurements of the five-minute amplitude using a $(3')^2$ aperture gave a value of rms $V_{rms} = 10.56$ m/s, which corresponds to $V_{rms} = 1.02$ m/s for a 0.8 $R_\odot$ aperture using the scaling procedure described above. This result indicated that even regions as large as 3' (130 000 km) are not totally independent. Much caution is justified both by the explicit assumptions about geometrical scaling and the implicit assumptions about the linearity of the magnetograph signal for velocity fields. With these cautions in mind, this result supports a global, rather than local, excitation mechanism for the five-minute oscillation.

Acknowledgments

The authors express appreciation to Robert Howard and Eric Fossat for useful discussions. Most of the observations described herein were performed by Eric K. Gustafson, with assistance from Steven D. Bryan. This work was supported in part by the Office of Naval Research under Contract N00014-76-C-0207, by the National Aeronautics and Space Administration under Grant NGR 05-020-559, by the Atmospheric Sciences Section of the National Science Foundation under Grants ATM74-19007 and DES75-15664 and by the Max C. Fleischmann Foundation.

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Figure Captions

Figure 1. Illustrations of how the peak power, noise power, resonant power, and average frequency are measured from an individual power spectrum. See text for further explanation. The power spectrum used in this example is the ensemble average of all power spectra, with weighting for length of observation.

Figure 2. Superposed epochs of resonant power, noise power, average frequency power, and peak power about polarity reversals of the mean solar magnetic field, as measured at Stanford.

Figure 3. Superposed epoch of power spectra of Stanford velocity data about polarity reversals of the mean solar magnetic field.

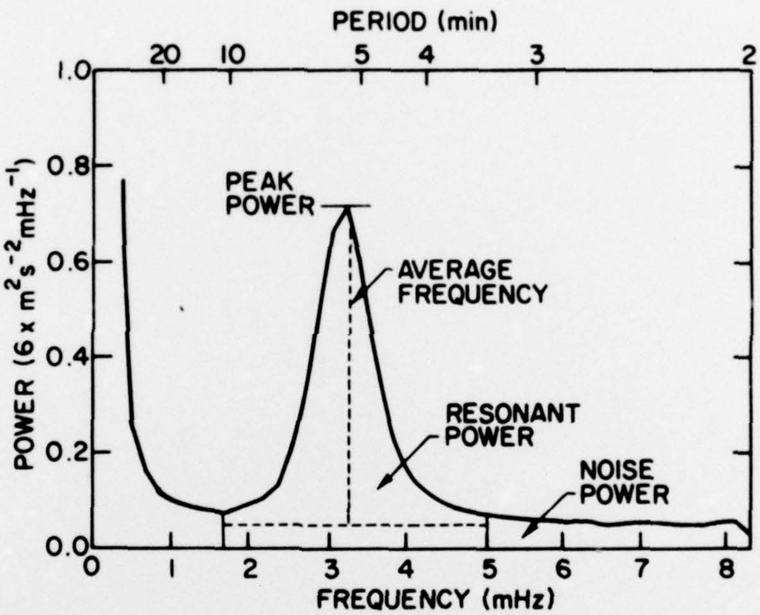

PERIOD (min)
20
10
5
4
3
2
1.0
0.8
0.6
0.4
0.2
0.0
POWER ($6 \times m^2 s^{-2} mHz^{-1}$)
PEAK POWER
AVERAGE FREQUENCY
RESONANT POWER
NOISE POWER
0
1
2
3
4
5
6
7
8
FREQUENCY (mHz)

Figure 1

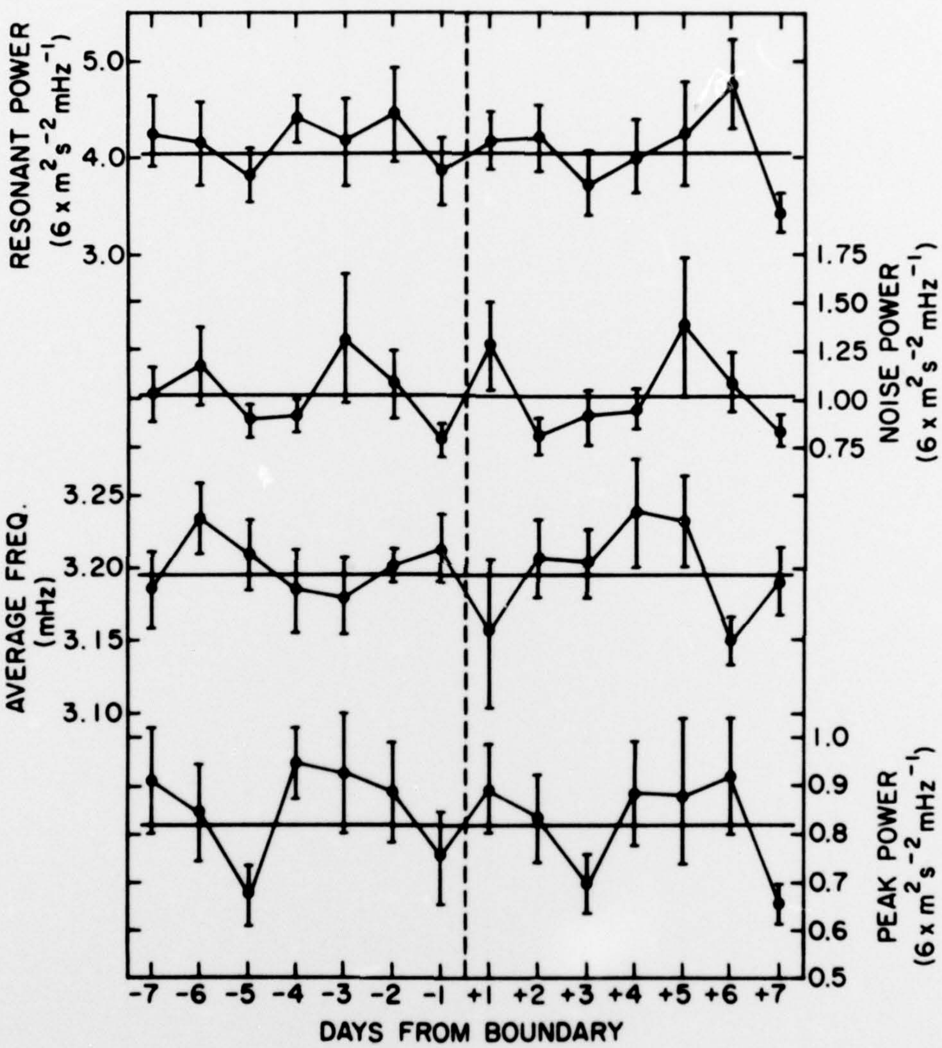
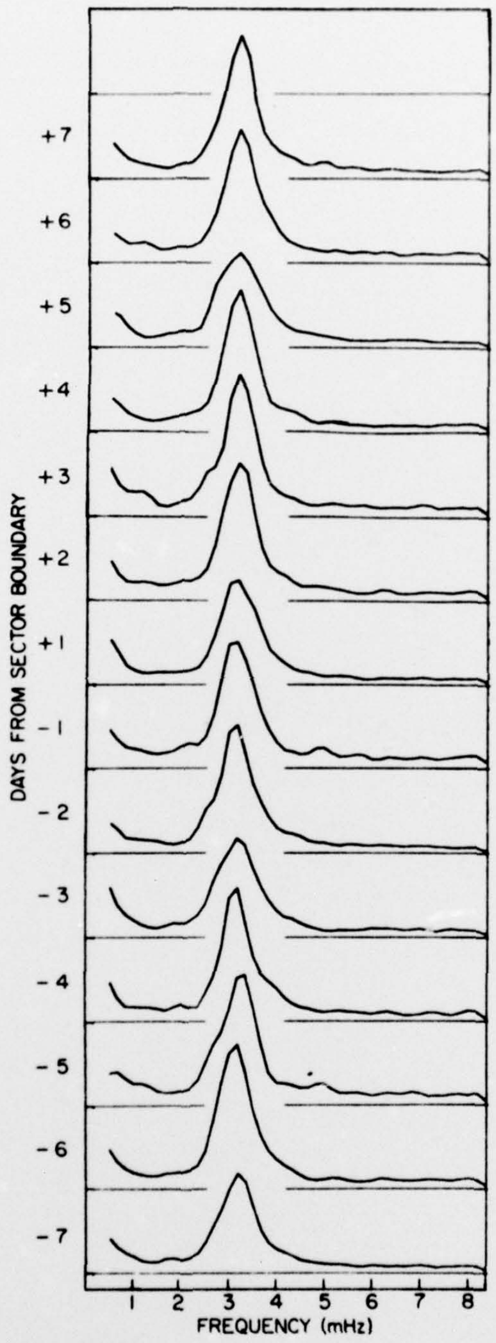

RESONANT POWER
(6 x m²s⁻²mHz⁻¹)
5.0
4.0
3.0
1.75
1.50
1.25
1.00
0.75
NOISE POWER
(6 x m²s⁻²mHz⁻¹)
AVERAGE FREQ.
(mHz)
3.25
3.20
3.15
3.10
1.0
0.9
0.8
0.7
0.6
0.5
PEAK POWER
(6 x m²s⁻²mHz⁻¹)
-7 -6 -5 -4 -3 -2 -1 +1 +2 +3 +4 +5 +6 +7
DAYS FROM BOUNDARY

Figure 2



DAYS FROM SECTOR BOUNDARY
+7
+6
+5
+4
+3
+2
+1
-1
-2
-3
-4
-5
-6
-7
1 2 3 4 5 6 7 8
FREQUENCY (mHz)

Figure 3